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14. ABSTRACT

This paper expands upon prior work on an entangled photon source generating six pairs of photons via spontaneous parametric down-conversion in a single pass configuration. Experimental results measuring entangled photons at 810 nm are shown and other wavelength regimes will be discussed. The design and fabrication considerations for a group velocity matched (GVM) superlattice photon source are discussed. An application of this source enables various multiqubit cluster states to be generated in a compact unidirectional configuration. This configuration simplifies the interferometric stability for any associated feed-forward methods required in photon-based quantum logic circuitry.

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A MULTIPLI-ENTANGLED PHOTON SOURCE FOR CLUSTER STATE GENERATION

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1. ABSTRACT

This paper expands upon prior work on an entangled photon source generating six pairs of photons via spontaneous parametric down-conversion in a single pass configuration. Experimental results measuring entangled photons at 810 nm are shown and other wavelength regimes will be discussed. The design and fabrication considerations for a group velocity matched (GVM) superlattice photon source are discussed. An application of this source enables various multi-qubit cluster states to be generated in a compact unidirectional configuration. This configuration simplifies the interferometric stability for any associated feed-forward methods required in photon-based quantum logic circuitry.

Key Words: quantum, entangled photons, spontaneous parametric down-conversion

2. INTRODUCTION

Photon-based quantum bits (qubits) continue to serve as one of the leading technologies for the demonstration of quantum computation. This is in part due to the desirable characteristics exhibited by photons; (i) room temperature operation, (ii) ability to transmit long distance, and (iii) relative immunity to environmental effects (decoherence). Typically these photons are produced pair-wise through the process of spontaneous parametric down conversion (SPDC) in a type I or type II nonlinear crystal. In the past decade there have been expansions beyond the single crystal approach with the goal of increasing the photon generation rate^{1, 2, 3}. Concurrently there has also been a push to obtain more qubits from a single source to meet the demand of quantum computation^{4, 5}.

In this paper we will expand upon our previous work⁶ on a multipli-entangled photon source which produces a diverse set of outputs states and is directly applicable to the generation of a multitude of cluster states. We will briefly describe the experimental testbed used for evaluation of our custom crystal source and the entangled photons produced. Next, we will show the experimental results obtained, and finally describe the applications of this source for the generation of cluster states.

3. BACKGROUND

Spontaneous parametric down conversion has proven to be the most reliable method of generating entangled photon pairs. Type I sources spontaneously convert one linearly polarized parent photon into two daughters, each having an orthogonal polarization to the parent. The spontaneous nature of parametric down conversion produces a ring pattern where each diametric photon pair shares the same parent photon. Because the type I process produces two photons of the same polarization which are path entangled. That is, detecting a photon (signal) in path A implies that its sister (idler)

can be found in the diametrically opposite spot⁷. This implies that in the polarization basis a mixed state $|H\rangle_1|H\rangle_2$ or $|V\rangle_1|V\rangle_2$ will be produced. Many experiments that require photon pairs, but not entangled pairs, use the output of a type I crystal as input to a more sophisticated experiment. Type I crystals are inherently birefringent, but the walk-off associated with these crystals is mitigated by the fact that the down converted photons are the same polarization; the delays that the signal and idler photons experience are the same. Type I sources have been used for many years in harmonic generation (SHG, THG) systems as frequency converters.

Kwiat first described a feasible source for SPDC-generated entangled pairs using type I β -BBO² (beta-Barium borate, BaB_2O_4). This consisted of a stacked pair of type I crystals rotated 90° relative to each other (Figure 1). This allows for the generation of two orthogonally polarized cones that overlap in space. Each crystal can only be excited by a certain linear polarization. The stack must be pumped by a beam made up of components that excite each crystal equally. That is, if the stack consists of an optic axis that is vertical in the first crystal, and horizontal in the second, the pump beam polarization must be oriented at 45° . The resulting superposition state is $|H\rangle_1|H\rangle_2 \pm e^{i\theta} |V\rangle_1|V\rangle_2$. It is important to note that there is a temporal delay associated with the down converted states due to the crystal's birefringence. Compensation depends on the wave packet of the pump photon.

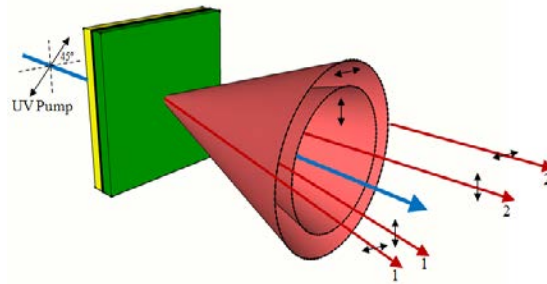


Figure 1. Kwiat's type I pair. Each crystal will spontaneously down convert a linearly polarized photon pair orthogonal to its pump photon. When specifically oriented, these down converted rings can overlap and create a polarization entangled pair.

Type II sources¹ down convert a linearly polarized parent photon into two orthogonally polarized daughters making them particularly interesting because the crystal is birefringent. One daughter photon will walk off faster than the other and lead to a noticeable spatial separation, and thus two intersecting cones (Figure 2). The walk off of type II crystals limits the length of the crystal because the extraordinary index of refraction will quickly bend light out of the crystal. Indistinguishable photons are produced in the intersections of the two cones. These two points form a superposition state of polarization $(|H\rangle_1|V\rangle_2 \pm e^{i\theta} |V\rangle_1|H\rangle_2)$ and have been exhaustively studied and used as inputs to more complex photonic systems.

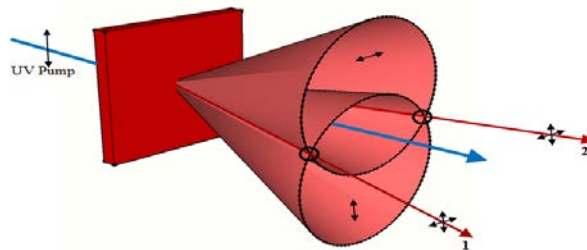


Figure 2. Standard type II down conversion. A linear pump beam spontaneously down converts to two photons, one of which has the same polarization as the pump. The other is orthogonal. The familiar double ring pattern is a product of the crystal's birefringence.

In a similar fashion to Kwiat's type I stack, Bitton et al.³ described a type II stack comprised of two crystals rotated 180° relative to each other (Figure 3). This allows the linear pump scheme to remain unchanged and yields one set of rings from either crystal. The set of rings entirely overlap each other and thus can yield an entangled photon pair of the same state as standard type II. Addressing the compensation is a necessary requirement with any birefringent crystals. A standard type II stacked configuration allows for greater pair production and more useable detection area. In this source as well as a type I stack, the fundamental size of the collection apertures become the limiting factor in the number of entangled pairs that can be collected.

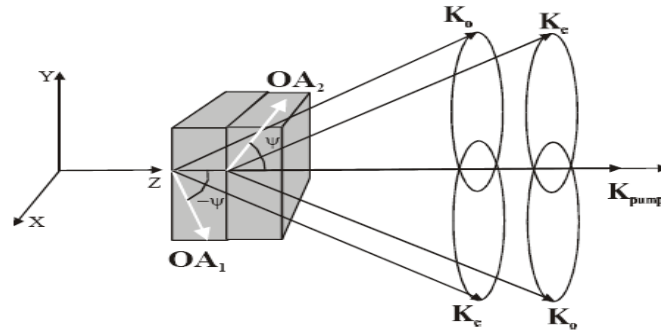


Figure 3. Type II crystal assembly as described by Bitton et al. The second crystal is rotated 180° relative to the first, resulting in two overlapping sets of cones with orthogonal polarization.

U'ren et al.⁸ described a type II crystal assembly (Figure 4a) that is designed for group velocity matching (GVM) of the pump and signal/idler wave packets, thereby removing any spectral distinguishability of the down converted photons. The assembly consists of a successive stack of nonlinear crystals (β -BBO, BiBO (Bismuth Borate, BiB_3O_6)) separated by a thin layer of compensating crystal (calcite (CaCO_3), α -BBO). This aims to slowly compensate different components (pump and down converted wave packets) such that by the end of the stack there is no spectral walk off. The need to spectrally filter post down conversion is mitigated by the symmetry of their joint spectral function (Figure 4b). Removing this requirement typically increases the useable count rate and overall efficiency.

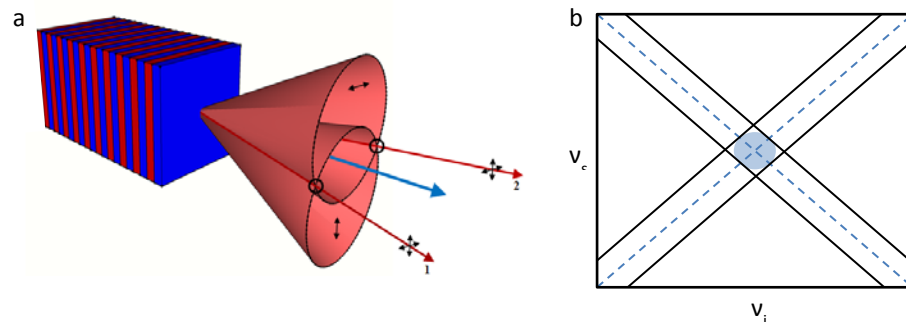


Figure 4. a. Type II custom assembly showing alternating layers of β -BBO (red) and calcite (blue). b. Joint spectral function of down converted wavepacket. This implies a maximally separable state.

Type I and II crystals are still governed by their spontaneous nature, and this becomes a problem when large numbers of entangled photons are required. In a typical configuration for the generation of greater than four photons a cascaded apparatus is used. For this setup either multiple crystals are used in succession, or multiple passes through a single crystal (Figure 5). This implies an overall increase in footprint size. Hyper-entanglement has been considered to mitigate

the spontaneous nature of down conversion by adding entanglement various degrees of freedom, not just polarization⁹. While this is effective it adds to the expense of larger physical hardware requirements and more complicated analysis processes.

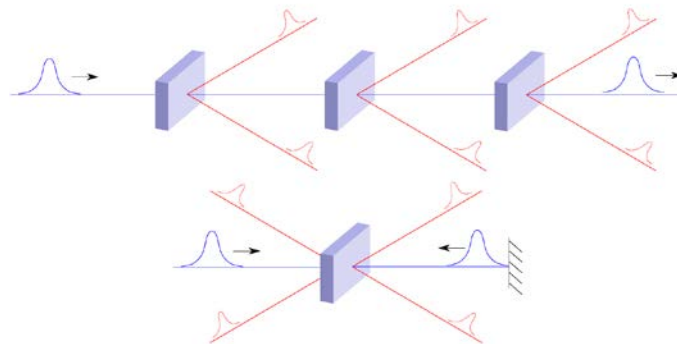


Figure 5. Cascaded and multi-pass crystal configurations for the generation of cluster states¹⁰.

In recent years there has been a paradigm shift in quantum computation with the need to migrate toward schemes that require only single qubit measurements. One-way quantum computation (cluster state) has facilitated this shift. Cluster state computation allows a predetermined sequence of single qubit measurements to determine the algorithm being evaluated¹¹. This protocol requires a highly entangled cluster state^{12,13} generated from a resource of qubits. Such a cluster state can be constructed by preparing each of the qubits into a state, $|+\rangle = \frac{1}{\sqrt{2}}(|0\rangle + |1\rangle)$, and applying controlled-phase gates to link the required qubits. Computation proceeds with a sequence of single qubit measurements whose results will classically feedforward to control the basis required for future measurements¹⁴. Cluster state computation allows for a practical resource reduction in qubits and hardware compared to other quantum computing methods.

4. THE SCHIOEDTEI MULTIPLI-ENTANGLED PHOTON SOURCE

4.1 SPDC custom crystal assembly

Our custom two-crystal assembly (designated as “Schioedtei” henceforth) design consists of a pair of type II non-collinear phase-matched SPDC crystals cut for degenerate down-conversion whose optic axes are rotated orthogonal with respect to one another. The pair of crystals is optically contacted with one another and a dual band (405/810 nm) anti-reflection coating applied to the two exterior faces of the assembly. Any type II material can be used to create an equivalent device. Our particular version that will be discussed here was constructed from two 8x8x2 mm type II beta-Barium borate (β -BBO, BaB_2O_4) crystals phase matched (at angles of $\theta = 41.9^\circ$, $\phi = 30^\circ$) for 810 nm spontaneous parametric down-conversion.

Exciting Schioedtei with an incident 45° polarized pump beam produces one pair of rings from each of the type II crystals. Each pair of rings is orthogonal to the other resulting in 12 intersection points (or simply “points”) where indistinguishable photons are produced. Referring to Figure 6, the indicated points marked 5, 6 (Bell pair #1 from crystal #1) and 7, 8 (Bell pair #2 from crystal #2) are the typical Bell states,

$|\psi\rangle_{5,6(7,8)} = \frac{1}{\sqrt{2}} (|HV\rangle_{5,6(7,8)} \pm e^{i\varphi} |VH\rangle_{5,6(7,8)})$. The points indicated by 1, 2, 3, 4 are the product of two bell states, $|\psi\rangle_{1,2,3,4} = \frac{1}{2} (|HV\rangle_{1,4} \pm e^{-i\varphi} |VH\rangle_{1,4}) (|HV\rangle_{2,3} \pm e^{-i\varphi} |VH\rangle_{2,3})$, produced from photons from both crystal 1 and 2 concurrently. Points 9, 11 and 10, 12 are $|VV\rangle_{9,11}$ and $|HH\rangle_{10,12}$ states produced from photons from crystal 1 and 2 concurrently.

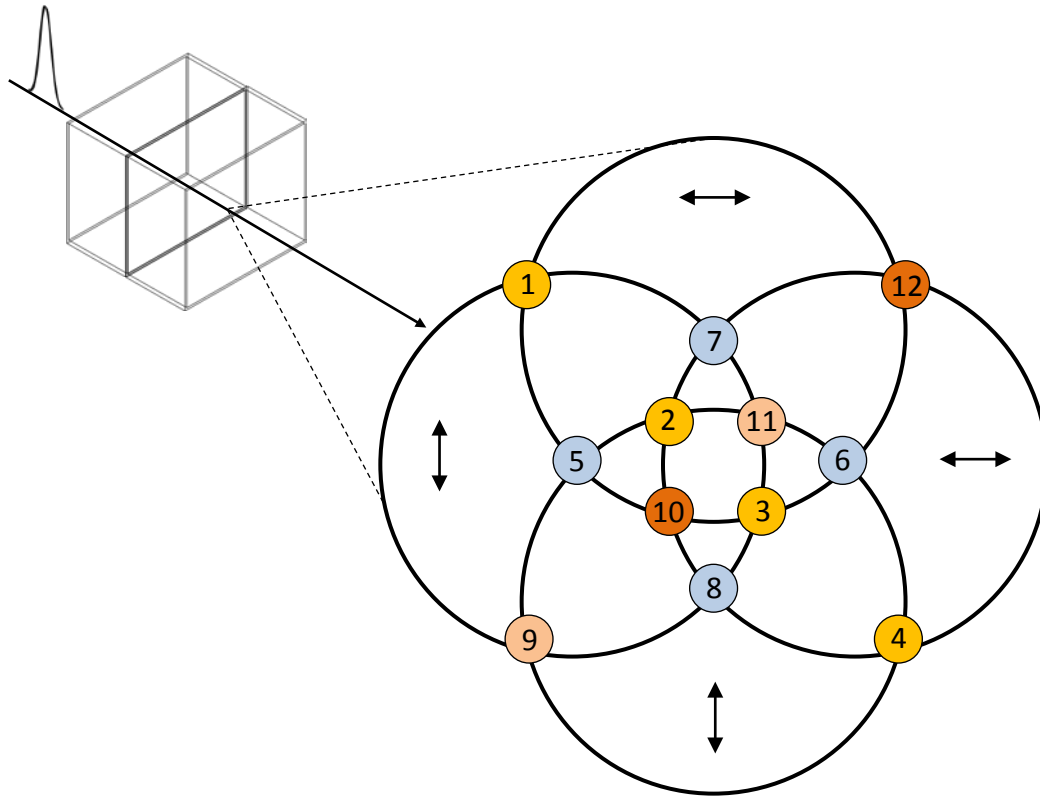


Figure 6. Type-II SPDC Schioedtei source. See text for discussion of the intersection points of the overlapping rings.

The experimental configuration for Schioedtei is shown in Figure 7. The testbed consists of a violet (405 nm) femtosecond pulsed pump source (Millenia PRO 15sJ > Tsunami 3960-15HP > Inspire Blue FM) with an average power of ~ 1.4 W, ~ 100 femtosecond pulses and a repetition rate of 80 MHz. The 405 nm pulses first pass through a ~ 12.5 mm quartz pre-compensator and a half-wave plate set to 22.5° to rotate the input linear polarization to the required 45° for equal excitation of the crystals before entering Schioedtei. Proper alignment of the crystal was accomplished with live images from a cooled CCD camera (Princeton Instruments Pixis 1024BR). The photons were collected in free space collimators located 1.5 meters behind Schioedtei. This distance is the minimum amount required to obtain the useable spatial separation required for detector access to the middle blue diamond of intersection points (5, 6, 7, and 8). The post-compensating crystals, inserted in the down-converted photon paths, are $8 \times 8 \times 1$ mm type II phase matched β -BBO (at angles of $\theta = 41.9^\circ$ and $\phi = 30^\circ$) as Schioedtei's orientation is non-collinear and there is no interaction between the pump and the compensators. These compensators could not be used for compensation of a collinear configuration as they were phase matched for SPDC at 810 nm when exposed to a 405 nm excitation beam.

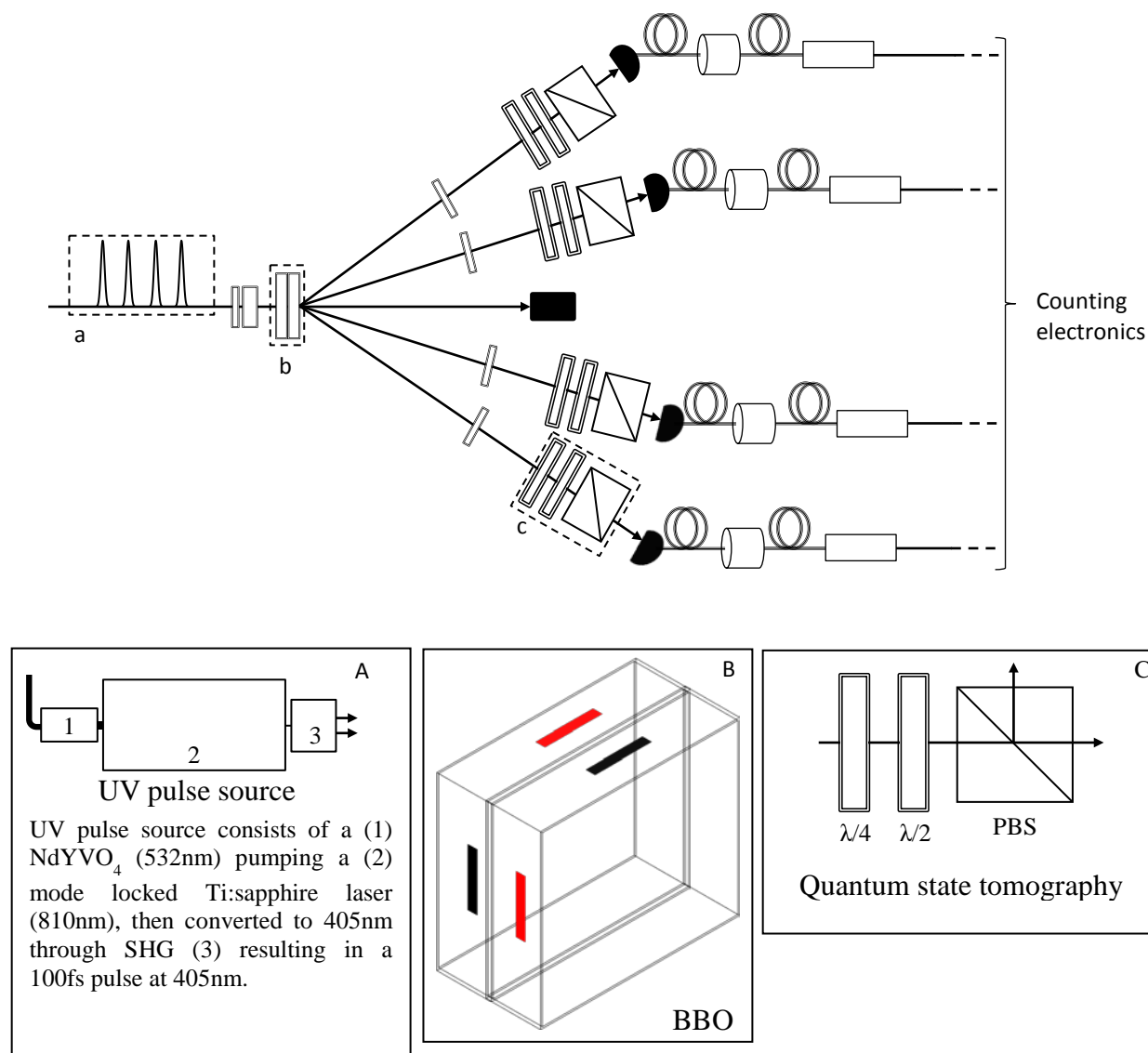


Figure 7. Experimental testbed to analyze the Schioedtei source.

Photon collection was accomplished via fiber coupled collimators immediately followed by 2 nm bandpass filters. The output of the bandpass filter was routed directly into fiber-coupled single photon counting avalanche photodiodes (APDs) (Perkin Elmer SPCM-AQ4C). Coincidence detection was accomplished by a four channel coincidence counting module (CCM)¹⁵.

A trio of false color CCD camera images of Schioedtei output is shown in Figure 8. The twelve overlap regions are clearly visible and the spatial symmetry of the output should be clearly noted. The orientation of the crystal assembly gives an approximate Gaussian profile on spots 5,6,7,8 and a slightly elongated profile for spots 1,2,3,4,9,10,11,12.

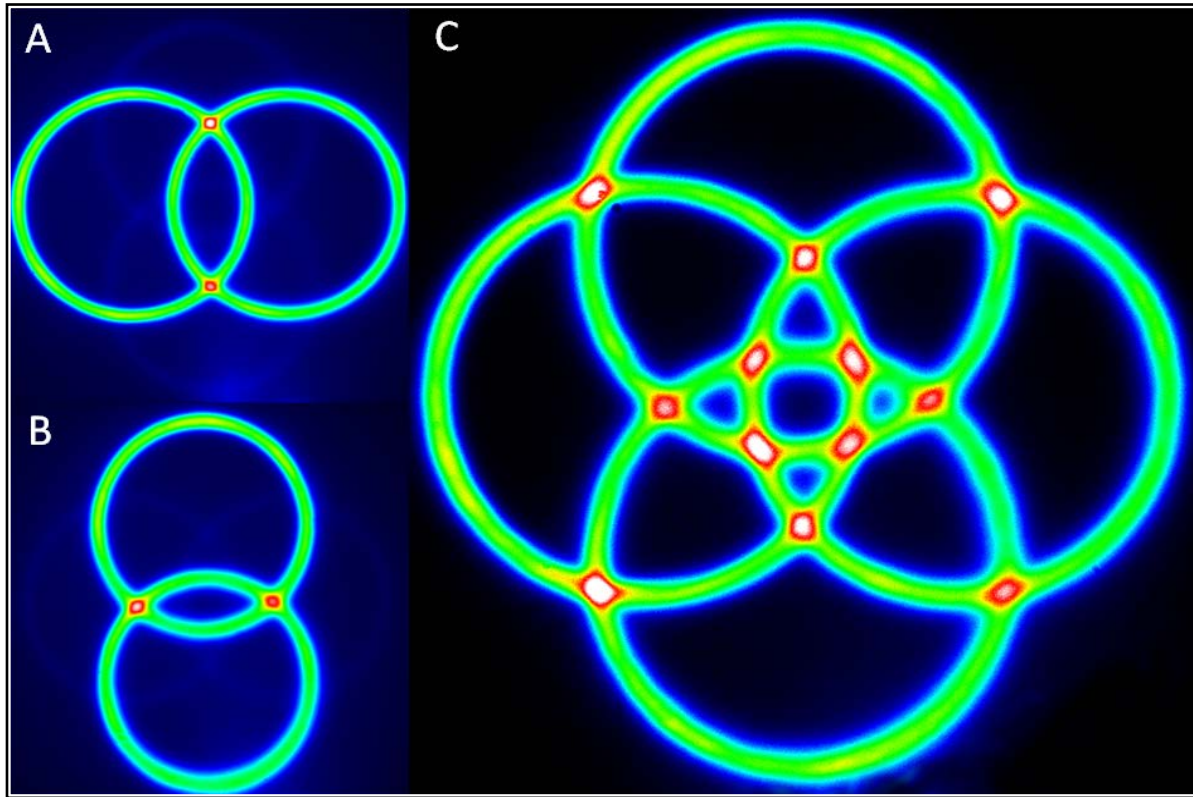


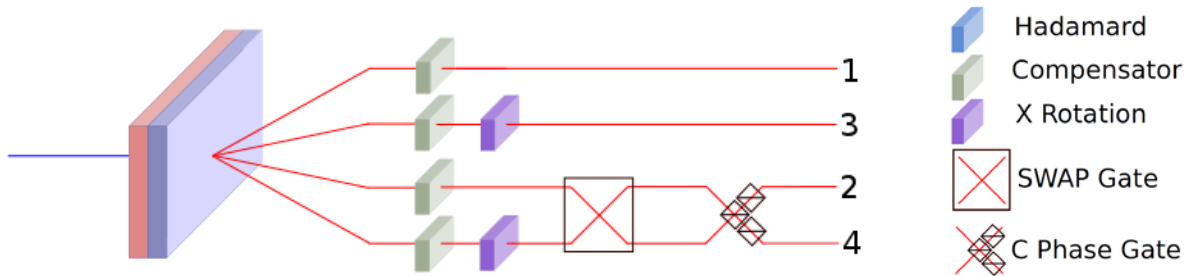
Figure 8. False color CCD images of custom crystal assembly (1 sec exposure). A,B are the type II non-collinear outputs from each individual crystal. C is the combined output from the crystal stack.

As stated, Schioedtei was constructed from β -BBO though any type II material can be used. Materials such as BiBO (Bismuth Borate, BiB_3O_6) have been shown to have a higher photon generation rate than β -BBO¹⁶ and this will be the next step for Schioedtei. Secondly, increasing the useable photon count rate in Schioedtei can be accomplished by factoring the GVM phase matching constraint⁸ into the crystal construction. A GVM-matched configuration¹⁷ is possible by alternating reduced thickness Schioedtei and α -BBO layers. α -BBO can be used as a compensator since there is no second order nonlinear effect in α -BBO crystal due to the centric symmetry in its crystal structure. Such a GVM source would provide the same up to six spatially separate entangled pairs as Schioedtei, while alleviating the need for spectral filtering of the photons. An increase in useable signal rates of 10x over a typical type II source is realizable with GVM matching.

4.3 Schioedtei source uses and applications

Another applicable area of extreme interest is in the generation of photon-based cluster states. Cluster states play a central role in the measurement-based one-way quantum computation approach^{11,12,13}. In this scheme, the entanglement resource is provided in advance through an initial, highly entangled multi-qubit cluster state and is consumed during the quantum computation by means of single-particle projective measurements. The feedforward nature of the one-way computation scheme renders the quantum computation deterministic, and removes much of the massive overhead that

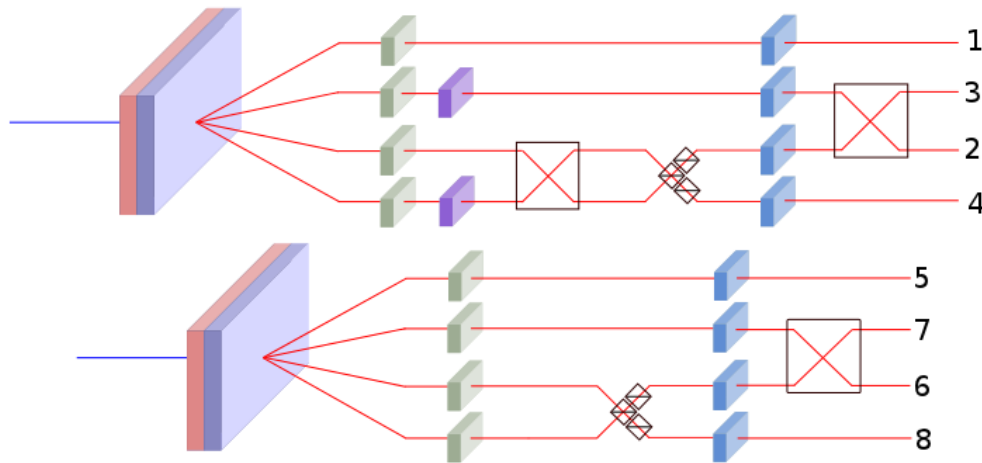
arises from the error encoding used in the standard quantum circuit computation model¹⁸. Figure 9 illustrates a scheme for utilizing the output of Schioedtei to generate a four photon cluster state, $|C\rangle_4$ ¹⁹. This particular example employs the spots 1,2,3,4 and requires insertion of two half-wave plates, a SWAP gate and a controlled-phase (CPhase) gate. This scheme could be expanded to include the other eight spots to generate even larger cluster states. Such experiments are currently being explored in-house.



$$|C\rangle_4 = \frac{1}{2} (|HHHH\rangle_{1,2,3,4} + |HHVV\rangle_{1,2,3,4} + |VVHH\rangle_{1,2,3,4} - |VVVV\rangle_{1,2,3,4})$$

Figure 9. Experimental setup for 4-qubit cluster state generation utilizing Schioedtei.

More complex cluster states can be constructed from Schioedtei with additional hardware. This includes, but is not limited to, the construction of box cluster states^{4, 11}. In fact Schioedtei is capable of producing two 4 qubit box states simultaneously by using 8 of the spots; 1,2,3,4 and 5,6,7,8. As the states Schioedtei outputs at these 2 sets of spots are different, slightly different preparation methods are required for the two boxes, as shown in Figure 10.



$$|\psi\rangle_{\text{BOX}} = \text{Swap}_{2,3} H_1 H_2 H_3 H_4 CZ_{2,4} \text{Swap}_{2,4} X_3 X_4 |\psi\rangle_{1,2,3,4}$$

$$|\psi\rangle_{\text{BOX}} = \text{Swap}_{6,7} H_5 H_6 H_7 H_8 CZ_{6,8} |\psi\rangle_{5,6,7,8}$$

Figure 10. Experimental construction of a 4-qubit box cluster state utilizing Schioedtei.

After the preparation is complete the two box states are completely equivalent. With additional preparation and resource photons these states can be used as the building blocks of larger states such as the 6 qubit butterfly network^{20, 21}. An

advantage of the Schioedtei configuration is the diversity of states that it is capable of generating. Schioedtei allows for the direct generation of the (unnormalized) state $|HV\rangle \pm e^{i\varphi}|VH\rangle$ along with the generation of the state $|HH\rangle \pm e^{i\varphi}|VV\rangle$ with the addition of a half-wave plate. In addition, separable states such as $|HV\rangle \pm e^{i\varphi}|VV\rangle$ or $|HV\rangle \pm e^{i\varphi}|HH\rangle$ can also be directly generated with clever combinations of the twelve output intersections and proper compensation.

5. SUMMARY

This paper has expanded upon our previous work⁶ on the Schioedtei source, a unique type II SPDC source design. Schioedtei generates up to six pairs of entangled photons per pass through the type II crystal assembly. This configuration surpasses the typical single entangled pair generated per pass found in standard type II SPDC sources. Concurrently Schioedtei generates a variety of states atypical of being produced from a single photon source. Useable photon generation rates (two and four photon) have been observed, thus showing its feasibility as a direct generation source of entangled photons for quantum optics/entanglement experiments. The six pairs of photons produced are directly applicable to the generation of linear, box, butterfly and a multitude of other cluster states. The utility of the Schioedtei source is (i) its reduced experimental footprint compared to standard multi-crystal/multi-pass experiments; (ii) it generates a variety of entangled/separable states; (iii) generated states are amenable towards cluster state generation.

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